ECL 193

ENGINEERING CASE STUDY

FROM THE ELECTRIC POWER INDUSTRY

ACCURATE LOCATION OF ARCING FAULTS

ON

PIPE-TYPE UNDERGROUND POWER CABLES

CLARENCE E. PRINCE, JR.

LAFAYETTE COLLEGE

THE DIVISION OF ENGINEERING

Lafayette College, Easton, Pennsylvania

ENGINEERING CASE LIBRARY

ECL 193A

ACCURATE LOCATION OF ARCING FAULTS ON PIPE-TYPE UNDERGROUND POWER CABLES

Part A

The Problem and Field-Lab Experimentation

This project had its start in chance observations. In addition to the fact that no other feasible scheme had been proposed, this scheme was actively pursued because of its essential simplicity. Whether that simplicity should be characterized as elegant or simple-minded remains to be seen, since the road to realization has been rocky indeed.

John J. Burns
Philadelphia Electric Company

Written by C. E. Prince, Jr. with the support of the Middle Atlantic Power Research Committee. Published by the Engineering Case Program with support from the National Science Foundation.

INTRODUCTION

Like many large urban electric utilities, the Philadelphia Electric Company has in service miles of hi-voltage (66 KV - 138 KV) underground power cables, and the difficulty of obtaining overhead transmission line right-of-way and considerations of appearance and convenience in crowded areas have created a trend toward still more undergrounding.

Location of faults on both the underground and overhead systems is the responsibility of the Service Maintenance Section, using methods and equipment either developed or specified by the Engineering and Research Department. Various methods, appropriate to the particular fault condition encountered, are applied and specific skills and techniques are continuously refined by practical experience.

In addition to a constant search for better methods and equipment to improve the precision of location and to reduce the time required for the procedure, a recognition in 1961 that the existing complement of techniques would probably be completely ineffective in the case of an as yet inexperienced, but by no means improbable, kind of fault on pipe-type cables generated considerable concern and led to the immediate search for a suitable location method.

More undergrounding of hi-voltage transmission and even residential distribution lines would undoubtedly take place in the future.

An article in Electric Light and Power in October of 1961, which recounted various techniques, had been seen by Service Maintenance engineers and passed around for others to read (Reference 1 in the bibliography). A meeting then took place in December, 1961, of engineers in the Research, Engineering Transmission and Distribution (T and D) Underground, Operating T and D Underground, and Operating T and D Service Maintenance Sections. John J. Burns was a part of this group.

"I think I was asked to attend the meeting," said John, "because several of the proposed techniques required some skill with special oscilloscopes and I had some knowledge about these."

This meeting resulted in plans for field testing of several methods and John prepared to participate and operate the oscilloscope after he had modified it to incorporate a sweep delay feature for better time resolution.

The greatest interest among the Philadelphia Electric engineers was in accurately locating faults in pipe-type underground cables in which arcing faults, which could not be found after removal of voltage from the cable, was expected to become a progressively more serious problem. Rapid and accurate fault location was of increasing importance (see Figure 1A, Appendix A).

AN ENGINEER AND "HIS BABY"

John J. Burns was an electrical engineer in the Research Division of the Engineering and Research Department of the Philadelphia Electric Company at Philadelphia, Pennsylvania. He graduated from the University of Pennsylvania in June of 1956 with two degrees, electrical engineering and physics, and came to Philadelphia Electric that fall. After a short period as a trainee, John spent five years in Field Engineering and one year in Protective Relaying. Since then, late 1961, he had been in the Research area.

The project discussed in this case began about the time John came to the Research Section. He worked on numerous projects simultaneously with the one presented here, sometimes leaving this work for long stretches of time due to other exigencies. As always, there was competition among various projects for man-hours. The development of a good procedure for fault location which could be easily used by field maintenance personnel was, however, a long-continuing challenge all his own, "his baby."

THE PHILADELPHIA ELECTRIC COMPANY

The Philadelphia Electric Company is a large, public utility, owned by 126,398 stockholders, and serving, in 1969, a 2,400 square mile area with a population of 3,900,000 people. At that time the Company counted 10,266 employees. Peak electrical load, on July 17, 1969, was 4,592 megawatts against a maximum capacity of 5,115 megawatts. Projected demands for electric power had resulted in authorization by the Pennsylvania Public Utility Commission to double this capacity, and plans were to construct $1.5 billion worth of new plant in 1970-1974, largely nuclear.

The Company is organized under a Board of Directors and President into nine divisions, two of which were

Engineering-Research and Electric Operations. John Burns was in the Research area and the engineers in Operations had responsibility for maintenance. Other company divisions were Legal, Finance and Accounting, General Administration, Personnel and Public Relations, and so forth.

Total operating revenue in 1969 was $440 million from sales of 21.9 billion KW-hrs electric energy, 67.6 billion cubic feet of gas, and 7.9 billion pounds of steam. Electric revenue was the largest part, $355 million. Payroll, fuel, and taxes accounted for $285 million in costs.

Some idea of P.E.'s underground cables can be gained from company records. By 1970, records showed, for 66-KV cable, 31 miles of solid type, 24 miles low-pressure, oil-filled, and 46 miles of pipe-type cable. For 132 KV, there were 20 miles installed.

UNDERGROUND CABLES AND FAULTS

John's experience in Field Engineering and his own further study had prepared him to grasp the problem, if not a ready solution.

Philadelphia Electric had in use three types of underground AC hi-voltage cables:

1. The so-called "solid" type, made up of one-to-three conductors insulated from one another by solid insulation (oil-impregnated paper) and surrounded by an over-all lead sheath--these were the oldest in service, up to 40 years.

2. The low-pressure oil-filled type--second oldest.

3. The hi-pressure, oil-filled, pipe-type cables--the newest and most predominantly used in 1970.

A description of 2 and 3 will be found in Reference 1A, Appendix A, along with an explanation of the difficulty of repairing cables with faults (also Reference 4 in the bibliography).

A "fault" in a cable may be of various types:

1. The conductor may be completely "open," that is burned or broken in two.

2. There may be a direct short-circuit, zero resistance, between a conductor and ground, the conductor's metallic shield--the "solid" fault.

3. There may be a fixed or varying resistance between the conductor and ground, of either high or low resistance character.

4. Lastly there may be the "arcing" fault which occurs only when the voltage stress between conductor and its shield goes above a limit, which may itself vary as the path character changes from moment-to-moment.

Most faults were of types 2-4, and for pipe-type cables, type 4. More modern protective relays were being used to clear faulted lines faster with less burning and reduction to low resistances at the time of failure. Thus, an increase in frequency of arcing faults was to be expected.

Cable sheaths are accessible only in manholes or at those points where the cable comes out of the ground, and conductors themselves are accessible only at terminations or "potheads." Fortunately, an underground three-phase cable was available for tests by Philadelphia Electric personnel and simulated faults could be "practice-located."

FAULT-LOCATING TECHNIQUE SPECIFICATIONS

John felt that due to the great complications of repairing a cable--long, very careful re-taping at splices--a location precision of at least 0.1% should be attained; e.g., a fault located 6000 feet away from a given manhole should be actually not more than 6006 feet nor less than 5994 feet away.

Further, it was clear that the method developed should be as rapid and independent of operator skill as possible. John knew some present techniques practically required a full-time specialized operator.

Of course, safety, since hi-voltages would probably be encountered, and inexpensive equipment were design specifications.

The minutes of the 1961 evaluation meeting recorded that "it was generally affirmed there was no single method known to the industry that can be relied on in advance to locate all the different types of faults that can occur." However, it was only natural that John considered it worthwhile to develop a method as universal as possible.

METHODS FOR LOCATING FAULTS

"We reviewed all then-known methods before beginning our own work," said John, "and found general agreement that arcing faults presented the greatest problem."

These various methods for all faults fell into two classes--tracer methods and measurement methods. Tracer methods depend on the ability to detect current directions on the cable sheath in the fault vicinity, when a test voltage is applied to the cable, or the detection of sonic vibrations created by an imposed arc at the fault. The difficulty of getting close to the cable and the interference caused by other electrical or acoustic noise made these methods difficult to apply on buried cables in crowded urban areas. However, for pin-pointing a fault after it had been roughly located by other means, the sonic detector looked interesting.

John felt measurement methods should be investigated first. Perhaps rough-locating schemes could be made more precise. Also among them was a method which had the appeal of universality--the Reflected Impulse, or "radar," method. The Electric Light and Power article said the method was very effective on open circuit or low resistance faults. High-resistance faults could be "burned down" by applying a hi-voltage DC for a period of time. For arcing faults, perhaps a large voltage could be used as the transmitted pulse and an arc created which could be reflected and measured. (See Reference 2A on page 8A of Appendix A, for a layout of this method.) Also the method was said to be about as accurate on resistive faults as a widely used bridge method, Murray Loop, which could not be used on arcing fault

Another method called Impulse Timing was noted as being applicable to arcing faults. It consisted of slowly raising a DC voltage applied to the cable until the fault point arced over. (See Reference 3A, Appendix A.) The ELP article, however, said that "it was thought that when it was developed, it could be extended for use on other types of cables"; i.e., the method clearly had not been proven out.

John was somewhat concerned about the oscilloscope methods as they demanded very precise timing of pulses. It was difficult to read pulses with that much precision, 0.1 µsec, since wave-forms varied. The sweep delay feature would help, but even with that, there were no nice, sharp right-angle corners to lay against a given time scale. This problem would have to be overcome.

John also reviewed the theory of propagating pulses on transmission lines. Polarities of wave forms reflected from open or short-circuited lines were important. But any solution of transmission line equations for such complicated geometry as a pipe-type cable was rather out of the question. John felt that amplification of received pulses would not cause much trouble since he needed only a few volts to display on the scopes, and pulses would be several 10's of KV in magnitude.

The literature search showed John that actual successful field experience with hi-voltage pipe-type cable was very limited. One article he found said that, "The failures that have occurred have been in splices and the explosions were sufficient to blow the lid off the manholes! Reports of the failures were received from the public only a few minutes after they occurred." (Reference 2 in the bibliography.) Clearly, somebody had to come up with something better!

FIELD-LAB EXPERIMENTATION

In his Interim Progress Report of June, 1967, John Burns stated, "This project had its start in chance observations.... In addition to the fact that no other feasible scheme had been proposed, this scheme was actively pursued because of its essential simplicity. Whether that simplicity should be characterized as elegant or simple-minded remains to be seen, since the road to realization has been rocky indeed."

First Work

The December 1961 meeting resulted in a plan to conduct in February, 1962, field trials on an underground pipe-type cable located in a PE substation, Plymouth Meeting. Weather interfered and delayed work until April. The objective was to incorporate a sweep-delay circuit into a Tektronix 507 scope and, using an impulse source, to try the Reflected-Impulse method. John felt at the time that this method, if it could be worked precisely enough, would give the most universality. The results of these April field tests were not good. (See Exhibit 1A on page 9A of Appendix A for John's first plans and Exhibit 2A, page 10A, for a report on these tests.)

Exhibit 3A, page 13A, shows pictures of traces recorded when attempting the radar method. The photos obviously support John's statement that poor resolution, i.e., hard-to-read records, was encountered. Each trace represents

trials for 40 KV, 30 KV, and 26 KV (DC volts) discharged from capacitors at the end of the line--discharging into the fault, measuring the return wave after break-down of the arc. John had no time to try the impulse-timing method.

The July 16th report (Exhibit 4A) summarized again the troubles encountered and indicates that lab tests on model circuits were initiated. These tests continued on and off during the rest of 1962 and first part of 1963. By this time John had definitely written off the radar method and was spending his effort to perfect the self-discharge, or impulse-timing, technique. The reason for this is made clear by studying Exhibit 3A and noting John's statements on the June, 1963, report (Exhibit 5A).

Experience With Commercial Equipment

In the fall of 1963, PE engineers made a decision to try out some equipment being sold by a sales engineer representing several commercial firms. This field test interrupted John's work in the lab, of course, since he had to participate and observe carefully. There were several tests on faults of all types using this equipment in September, October, and November. PE was particularly interested in this equipment since the makers said it had an effective acoustic pick-up which could be used to pinpoint the arcing fault. However, John felt that the basic technique used of discharging into the fault was unreliable.

Minutes of a meeting on October 16, 1963, record:

> J. J. Burns stated that his research into similar equipment ran into a real problem because of the time delay which occurs between impulse and the time that the fault actually flashes over. A difference of a few microseconds can result in a considerable error in locating the fault.

Skeptical as to the possibility of any positive results, John attended all the tests and operated the hi-voltage voltage scope, Polaroid camera, set-up, and so forth. In the course of some tests, several photos similar to Exhibit 6A, Appendix A, were taken. John noted these carefully.

It was found that in order to have the arc-over point more or less consistently occur at the same point in the wave-form, a very much higher peak DC voltage pulse had to be applied than really necessary to break down the arc.

"Final Conclusions" of a report in December, 1963, state:

1. The sound pick-up equipment, as demonstrated, has no practical value on pipe-type cable faults. It may have some value when used on buried cable.

2. The tests conducted at Plymouth Meeting were unusually severe, in that many variables have been built into this experimental cable installation and at this time no one is sure what conditions exist at the various joints.

3. The impulse-photo technique as demonstrated, did not provide indications reliable enough to locate faults in pipe-type cable.

4. The limited tests made indicate that an impulse to flashover voltage ratio of 5 or more will be required to assure satisfactory results with this technique, assuming that all other factors are satisfactory. A voltage limitation of 80 KV on any manufacturer's equipment will be far too low.

5. The search must be continued for a reliable method to locate faults on pipe-type cables up to and including 230 KV.

This series of field tests had taken a great amount of effort. The commercial equipment had given negative results on arcing faults in pipe-type cables, and indeed had located in several cases only the other end of the test cable, not at all the real fault!

John carefully recorded all tests and wrote reports to the head of his research section. Frequent discussions also were held. The project remained a keen interest of Operations Transmission - Distribution (Underground) Section and the Engineering and Research Section.

More Lab Work

Following the series of tests in the fall of 1963, John decided to pursue his own lab work centering around the impulse-timing or self-discharge method. Observation of many test photos had created in his mind several possibilities to try out in order to get "cleaner" scope traces and better timing. Year's end, 1963, saw a comprehensive report to his senior and a proposal for more construction and testing in lab of a system.

Transmission Line Basics (Appendix A, page 17A) reviews some fundamental transmission line theory which helps in analyzing scope pictures.

APPENDIX A

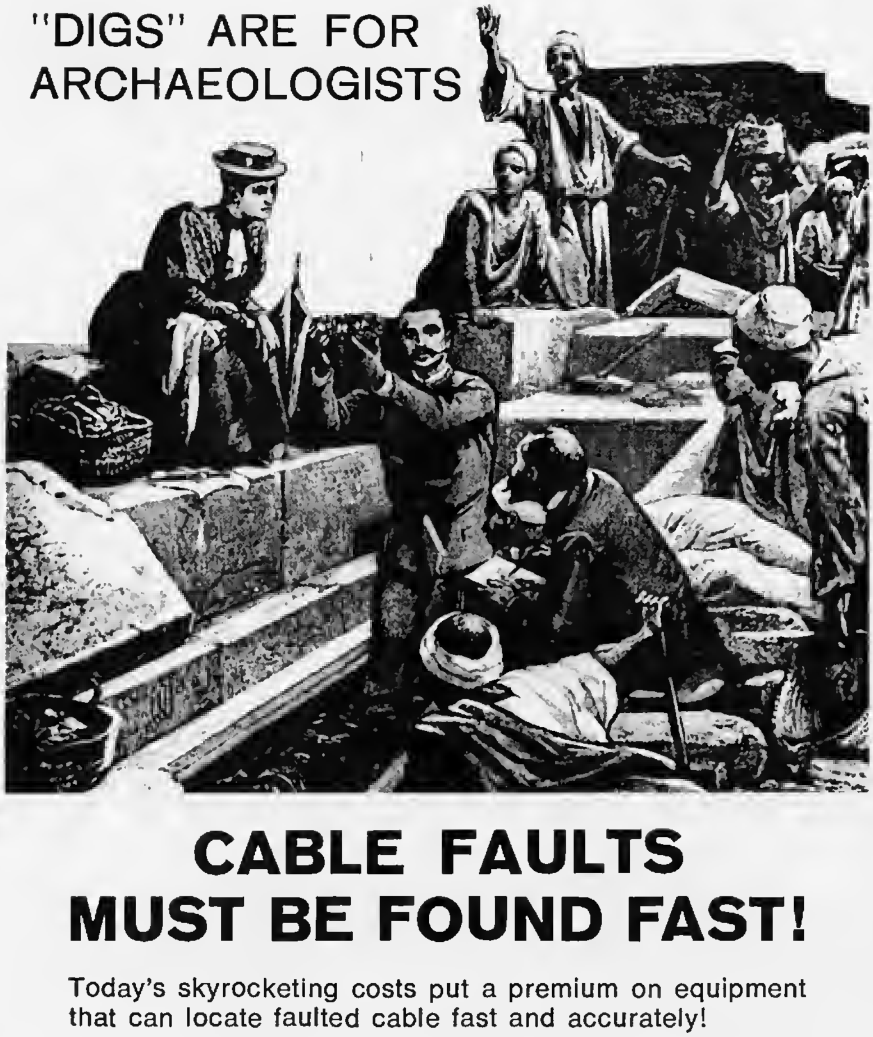


Illustration by courtesy of the J. G. Biddle Co., Plymouth Meeting, Pa., makers of fault-locating equipment.

Figure 1A

REFERENCE 1A

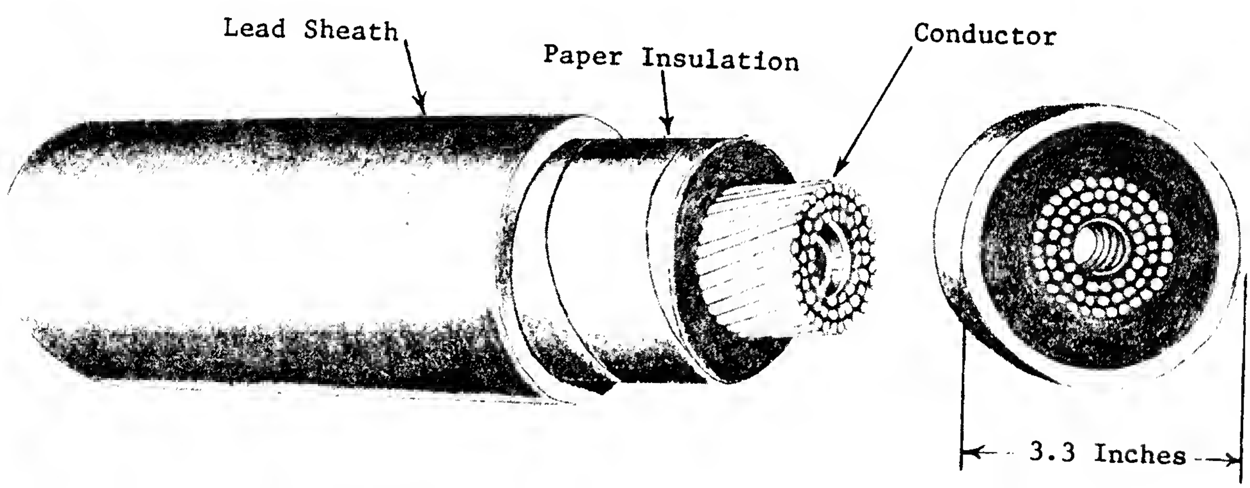
UNDERGROUND LINES

(Excerpted with permission of the Federal Power Commission, from Underground Power Transmission, Report to FPC, 1966, pgs. 20-22, 25.)

Types & Uses

The commonly used underground transmission cable has copper conductors covered with high quality insulating paper. This paper is kept saturated with oil to improve its electrical insulating properties. There are two major types of cable--"low pressure oil-filled" and "pipe-type."

In the "low pressure oil-filled" cable a protective lead sheath surrounds the insulation to keep moisture out and the oil in. The oil, at low pressure (3 to 20 pounds per square inch), penetrates the insulation from channels located in the cable. In single conductor cables, a "hollow core" in the multi-stranded conductor provides this path (Figure 1). The oil is not normally used for cooling

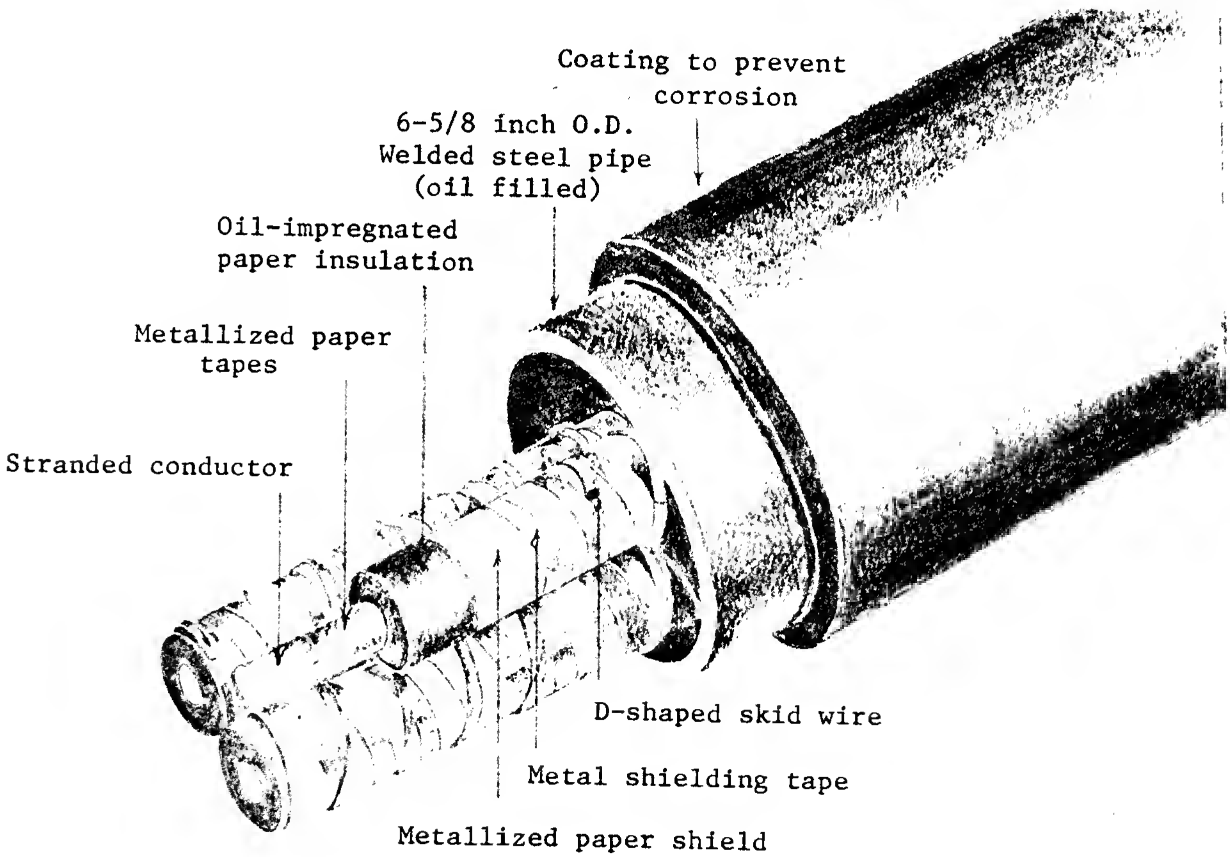


Oil for this 138,00-volt, Single-conductor, Low-pressure Oil-filled Cable is Carried Through the Opening in the Center of the Conductor.

Figure 1

cable sections are joined by splicing. The manhole must be large enough to permit the cables to be pulled into the ducts and to allow for linear expansion of the cables, must have an entrance at ground level, and should be near an all-weather road that would provide access for cable trucks for installation and maintenance. Low pressure oil-filled cable is used predominantly where the terrain is relatively flat and where multiple-ducts can accommodate several cable circuits. If the difference in elevation is too great, the internal oil pressure could rupture the cable sheath or cable terminals. To prevent this, special "stop" joints are installed at critical changes in elevation to sectionalize the cable into separate sections to keep the oil pressure within tolerable limits.

With the "pipe-type" cable, three single conductor, paper insulated cables are located inside a single buried steel pipe (Figure 3) filled with oil at high pressure (200 pounds per square inch). Pumping plants are needed to



This 138,000-volt, Three-conductor, High-pressure, Oil-filled Pipe Type Cable is Typical of Those Used Most Widely in the United States Today.

Figure 3

maintain this pressure and to compensate for the effect of temperature changes. Nitrogen gas, instead of oil, is sometimes used.

Typically, this type of cable can be pulled into half-mile lengths of pipe. As a result, manhole, cable pulling, and joint construction costs are reduced. Also, the steel pipe provides a high degree of mechanical protection to the cables, adding to their reliability. After a recently completed industry research project to develop 345,000 volt cable, the pipe-type (at this voltage) was installed in New York City.

Although the basic principles of cable design, installation, and operation may appear simple in concept, they are difficult to realize in practice. For example, high voltage cable splicing requires meticulous attention to details. Oil saturated tapes must be carefully wrapped over the joined conductors in a particular arrangement to distribute the electrical stress evenly along the insulation. Moisture must not enter during the splicing operation. Oil paths must be provided, shielding tapes restored, and protective sheaths replaced. Splicing a cable is a painstaking and meticulous procedure. Requirements for cleanliness and precision are similar to those usually visualized for a surgical operation. Each splicing for a 345,000 volt cable may take eight 24-hour days or more. Oil reservoirs and pumping systems and their piping and controls for supplying oil to the interior of a high voltage cable must be built for reliable continuous service. All of this contributes considerably to the high cost of underground cable installations.

All underground transmission cables require trench digging for the installation of ducts or pipes. The surrounding earth must dissipate the heat generated in the cable. Where the heat transfer capability is poor, special soil may be placed around the cable to remove the heat, but this involves a considerable increase in cost. Cable lines must be firmly supported and the earth around them must not shift, so the backfill must be placed carefully. In undeveloped areas trenching may be relatively easy; in rocky, swampy, or congested areas it becomes a major problem. Power demands are usually heaviest where there are structures, roads, and utility services of all kinds. A cable system may compete for underground space with water and gas pipes, sanitary sewers, storm sewers, telephone cables, steam pipes, and subway tubes. Threading new power cables through an existing maze of other pipes and lines is a costly undertaking.

Because of factors such as differing underground conditions and power demand densities, it is not possible to meet all needs with one cable type. A selection of the best cable type must be made for each project.

Repair

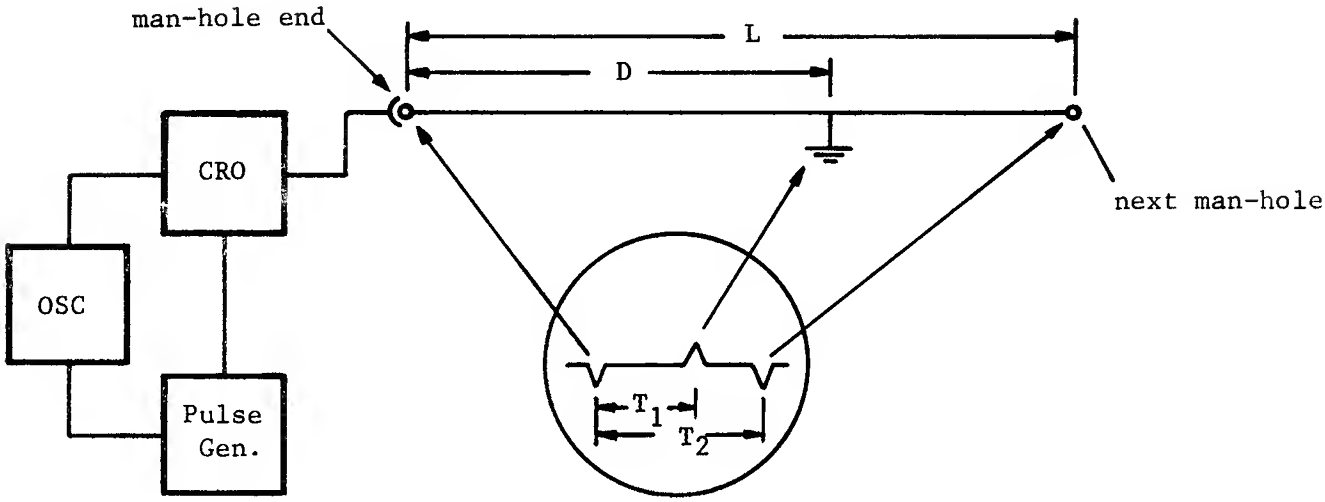
In general, underground lines are free from weather problems and, therefore, have fewer interruptions than overhead lines of the same length. Cables, because of their concealed location, are subject to accidental damage by construction crews, or others, who puncture or injure them while digging. Cable lines, like any other metals buried in the ground, will corrode; hence, they are often covered with special corrosion resistant material. This is costly, and sometimes additional and more complex preventive methods must be used.

When failure occurs in a cable, the duration of outage may be from a few days to several weeks. To understand why so much time is required, consider the steps in repairing a pipe-type cable. First, the location of the failure must be pinpointed; it is usually not detectable by aboveground observation and requires the use of specifically designed fault-finding equipment. Then the pipe is exposed by excavation, and the oil is frozen (-50°F.) to prevent its flow. The pipe is then removed from the faulted area of the cable, and the damaged section of cable replaced and spliced by the very meticulous process previously described. The pipe is then replaced and the ground returned to its original condition. Fortunately, the failure rate of pipe-type cable is low.

REFERENCE 2A

REFLECTED IMPULSE (RADAR) METHOD

(Courtesy of Electric Light and Power, Oct. 1, 1961, pg. 21)



Technique: "Elapsed time appears as a time difference between the transmitted and reflected pulse on a calibrated trace on a CRO. Calibration is done by switching to a non-faulted conductor and using the end of the cable to adjust the calibration circuits."

Relations: $2D = V_c \cdot T_1$ (where V_c is velocity of propagation on the cable)

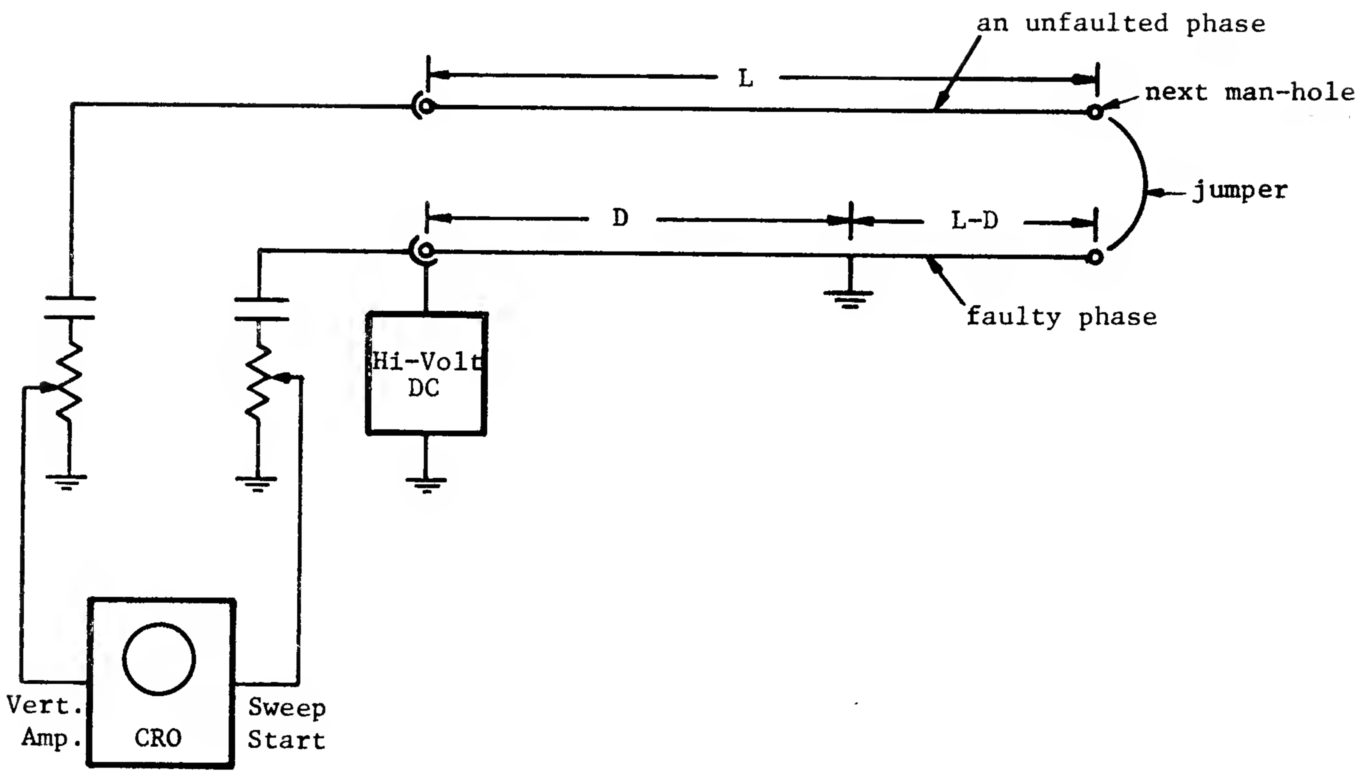
$2L = V_c \cdot T_2$

$D = L\frac{T_1}{T_2}$ (if L is known)

REFERENCE 3A

IMPULSE-TIMING METHOD

(Courtesy of Electric Light and Power, Oct. 1, 1961, pg. 22)



Technique: Calibrate by applying a low-voltage impulse to the faulty phase terminal and measure the time for the impulse to complete the entire circuit (2L distance). Now raise the voltage on the cable until the fault flashes over. The time recorded is then the difference between the time to travel D and 2L-D.

Relation:

$$V_c = \frac{2L}{T_{cal.}}$$ (velocity of propagation)

$$K = \frac{2L-D}{V_c} - \frac{D}{V_c}$$ (time difference measured)

$$D = L - \frac{KV_c}{2}$$

EXHIBIT 1A ECL 193A

Has been Typed
No Carbon for file

RESEARCH PROJECT

Project No. 4365 W.O. 5255-523 Date 1/8/62

Subject Oscillographic Fault Location {Does Not include Hi-Volt Bridge}

Project Engineer JJB File Fault Locating Equip. 1948/

Objectives

To adapt the Tektronix 507 Scope for use in locating high-voltage cable faults in conjunction with the Früngel impulse test set.

Background

Present methods of fault locating in P.E.Co are of doubtful efficacy for high-resistance faults in pipe-type cable. A high-speed high voltage CRO and suitable voltage dividers are available in the Co. To improve the ~~efficiency~~ precision of measurement, it is proposed to provide for a delayed scope sweep and to test the practicability and accuracy of the technique on the 66-kv Oilostatic test loop at Ply. Mtg. Sub.

Sched:

Jan '62 - Modify trigger ckts of 507 Scope
Feb '62 - Fault-location tests at Ply Mtg
Mar '62 - Formulate recommendations for commercially available equip or abandon technique.

Completion

Apr. '62 5 x 8 Memo

CABLE FAULT LOCATING

PRELIMINARY FIELD TRIALS

During the week of April 9, 1962, fault-locating tests were conducted on the experimental Oilostatic cable installation at Plymouth Meeting Substation. Both bridge and impulse methods were investigated, with the mobile Isolex test set and impulse generator used by Service Maintenance Section as the power source. Inclement weather limited the amount of testing that was accomplished.

With a constant high-resistance fault, simulated by an arrangement of wire-wound resistors aggregating 0.75 megohm, approximately 25 kv was applied to the Morse-Newhall bridge to produce a suitable measuring current. Two circuit arrangements were employed, as illustrated in Diagrams 1 and 2.

With the three phase conductors connected in series, as in Diagram 1, and with a simulated fault at point S, no balance could be obtained. Possible reasons for this difficulty are now being analyzed.

With two phase conductors in series, as in Diagram 2, balance was obtained for simulated high-resistance faults at points X, Y and Z. The bridge measurements are summarized in Table I.

A bridge balance was not possible when an arcing fault was substituted for the resistive fault. Voltages up to 40 kv were used in an unsuccessful effort to maintain a steady arc. Time did not permit attempting to reduce the fault to a constant resistance.

Fault location by impulse reflection was attempted using a high-frequency oscilloscope connected to a voltage divider at the surge generator location. Tests were made both on a single phase and on the three phases connected in series. Solid, high-resistance, and arcing faults were applied to the circuit. The results were in many respects disappointing, probably because of shunting of the received reflection by the capacitance of the impulse generator. In reportedly successful use of this method by another utility, the voltage divider was located at the end of an unfaulted phase of the line being investigated, with that phase tied to the faulted phase at the end remote from the impulse generator.

The high-voltage test set was used as the impulse generator. Measurement of fault-initiated impulses as the cable was slowly brought up to the fault flashover level was not attempted.

The delayed scope trigger circuit was successfully employed and the increase in precision thus obtainable was demonstrated, although the uncertainty of the fault indication made the record extremely difficult to evaluate.

No techniques using sonic measurements were attempted.

TABLE I

Test No.	Bridge Connections A to	Bridge Connections B to	Fault at	Measured Reading	Calculated Reading*	Error Feet	Error %
1	B ø	C ø	X	512.8	511.7	5	0.11
2	C ø	B ø	X	500.3	488.3	54	1.2
3	B ø	C ø	Y	492.2	490.0	10	0.22
4	C ø	B ø	Y	519.1	510.0	40	0.9
5	B ø	C ø	Z	980.7	978.0	12	0.27
6	C ø	B ø	Z	23.7	22.0	7.5	0.17

*Total loop resistance was measured as 0.1059 ohm, which, subtracting the measured resistance of the connecting leads, yields a calculated conductor temperature of 7°C. Calculations were made using this temperature and the recorded lengths and conductor sizes of the installation.

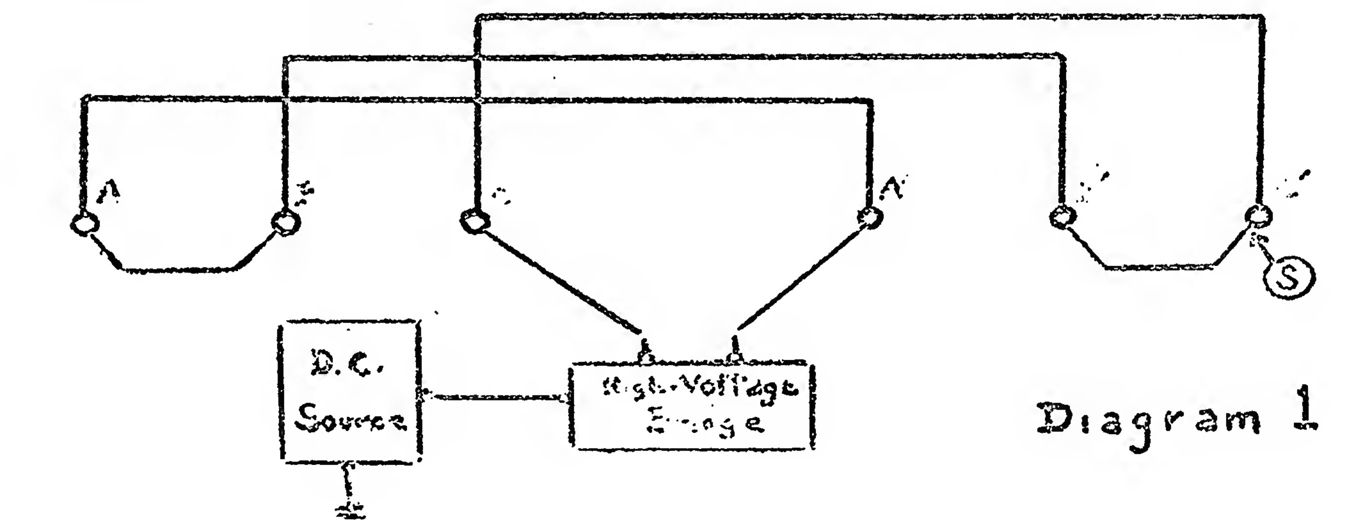


Diagram 1

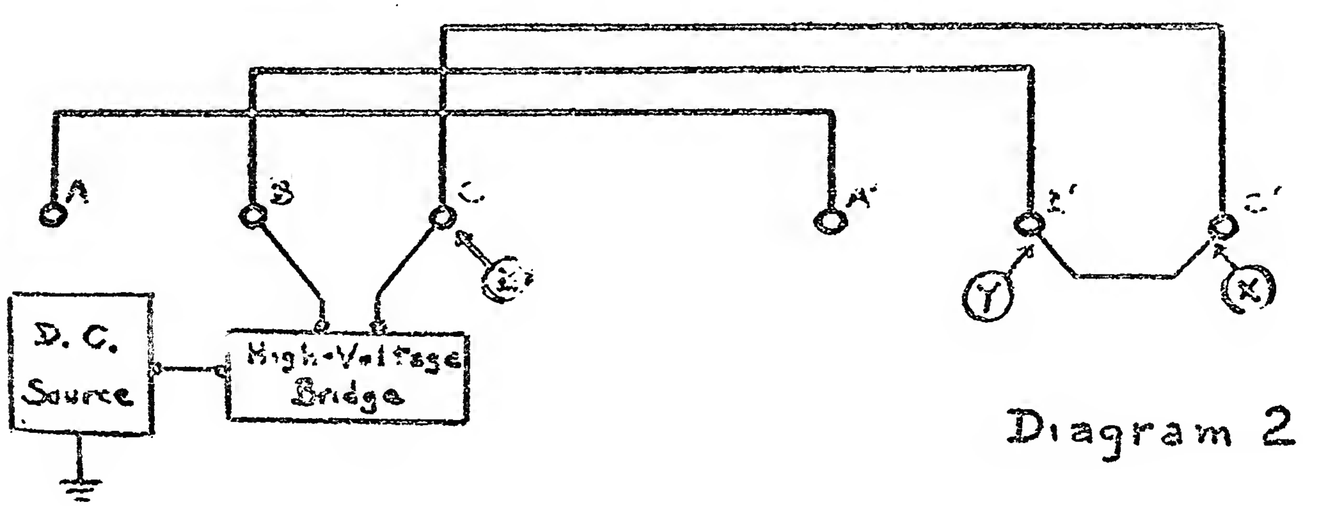


Diagram 2

The precision of the high-voltage bridge measurements described above falls short of the expected 0.1%. It is thought that this may be due in large measure to variations in contact resistance of the connecting leads. Standard safety grounds were used for the bridge leads, and the adapter pads were polished prior to making the connections. It is probable that significantly better results can be obtained with silver-plated lugs and high-pressure connections which would require the fabrication of special bridge leads. Careful procedure is necessary to verify that good connections have been made. The possibility of error caused by unbalanced capacitance charging current at rectifier ripple frequency is to be investigated. It appears that a bridge measurement cannot be made on an arcing fault unless it is reduced to a constant resistance.

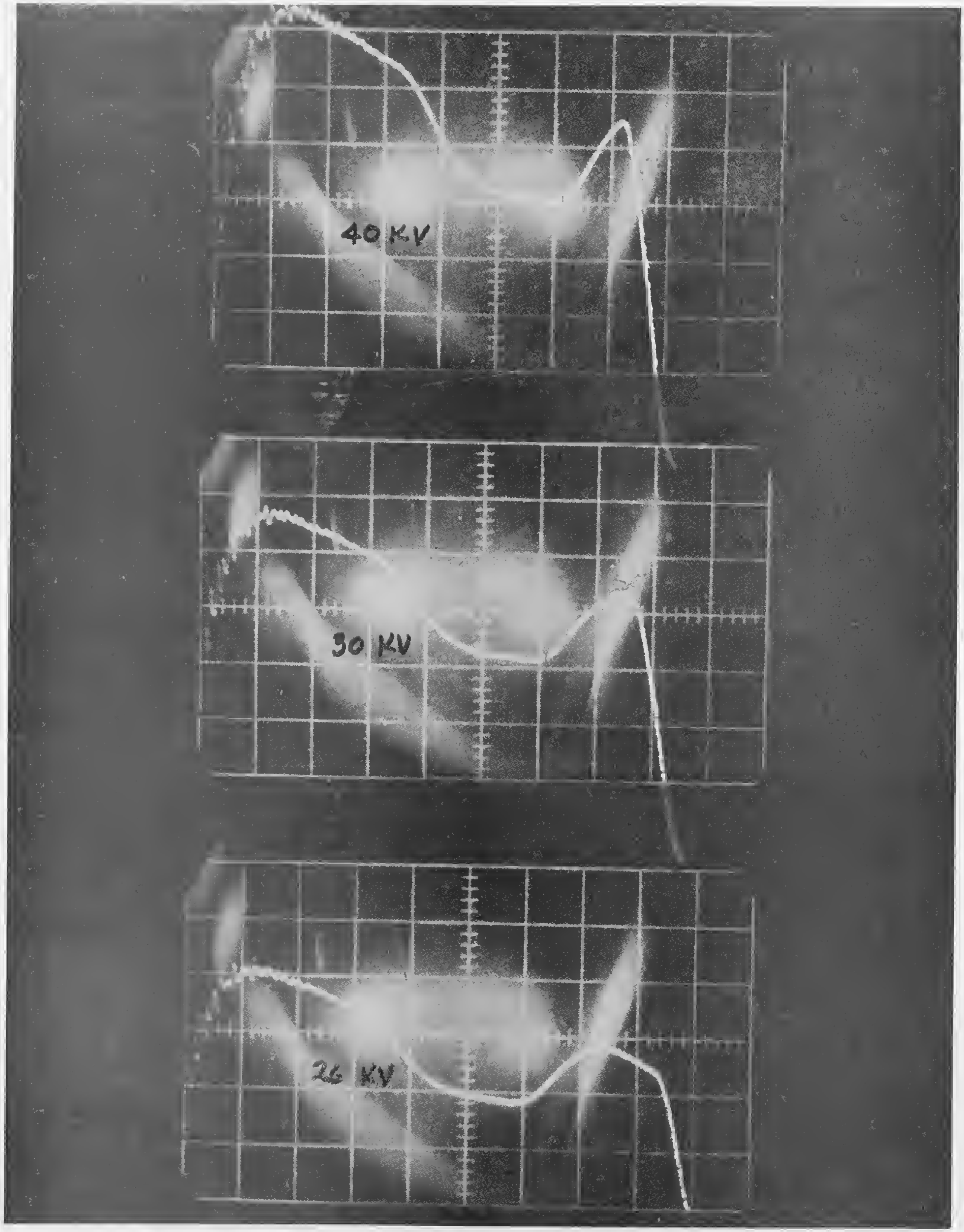
The one form of oscillographic impulse technique which was used is not promising. Several variants of this technique exist and are to be evaluated. It is hoped that much of this evaluation can be made on model circuits in the laboratory, although simulation of the intercalated helical shield may involve some difficulty.

A meeting is scheduled for 10:30 A.M. Friday, May 4, 1962, in the office of W. J. Johnson, to discuss progress made so far, and to survey possible future lines of investigation.

J. J. Burns

JJB:LS

EXHIBIT 3A



Photos Taken Using Impulse-Radar Method. Hor. (1 μsec/cm); Vert. (4.2 KV/cm) Discharging into fault.

EXHIBIT 4A
RESEARCH PROJECT STATUS REPORT

ECL 193A

Project No. 4365 W.O. 5299-923 Date 7/16/62

Subject OSCILLOGRAPHIC FAULT LOCATING

Project Engineer JJB Cable - Fault Locating Equipment

Developments Since Last Status Report Dated

Breadboarded delay circuit successfully used in field tests at Plymouth Meeting April 10 and 11. Poor resolution of the indication of fault location and erratic fault time-lag indicate need for further refinement in technique. (Int. Items 4/9/62, Memo 5/1/62, Meeting 5/4/62.)

Present Status

Investigation of model circuits to be undertaken in laboratory to seek explanation of difficulties encountered in field and to determine optimum techniques for next field trials.

Schedule Changes

8/1/62 - Construct and investigate model circuits.

10/1/62 - Schedule further field trials.

Completion:

12/1/62 - Incorporate into general fault-locating study.

EXHIBIT 5A

ECL 193A

RESEARCH PROJECT STATUS REPORT

Project No. 4365 W.O. E.A. C.A. 5299-923 Date 6/26/63

Subject Oscillographic Fault Locating

Project Engineer JJB File Fault Locating Equip.

Developments Since Last Status Report Dated 7/16/62

Erratic fault time-lag experienced in Plymouth trials on 4/11/62 has led to investigation of techniques of arc-over of fault on D.C. charging rather than surge-generator impulse. Improvement of resolution is being persued by method using biased pulse transformer.

Present Status

Active. Promising results are being obtained in the laboratory and further refinements are in progress. As much investigation of sonic techniques as time permits will also be made. E.A. will be prepared covering this year's activity.

Schedule Changes

8/15/63 Further field trials.

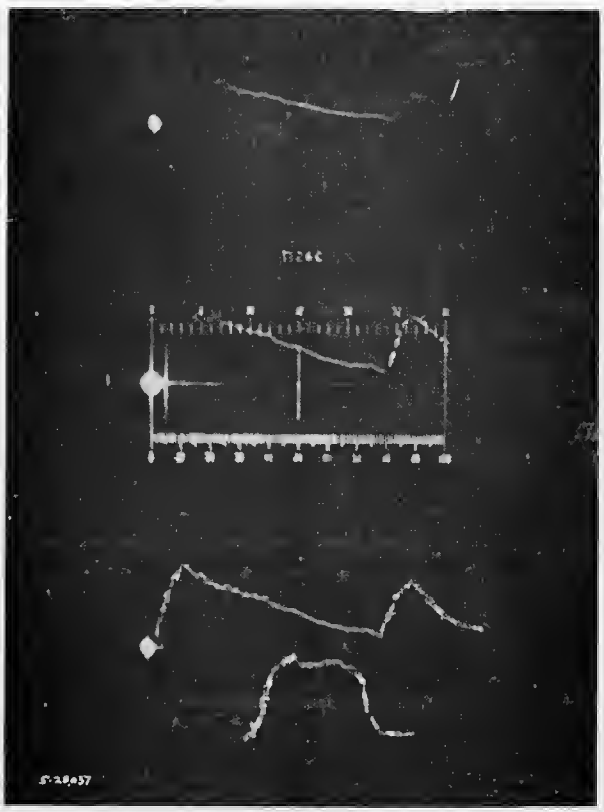
10/1/63 Memorandum on results to date.

Completion:

Dependent on results.

ESH:blm
6/28/63

EXHIBIT 6A

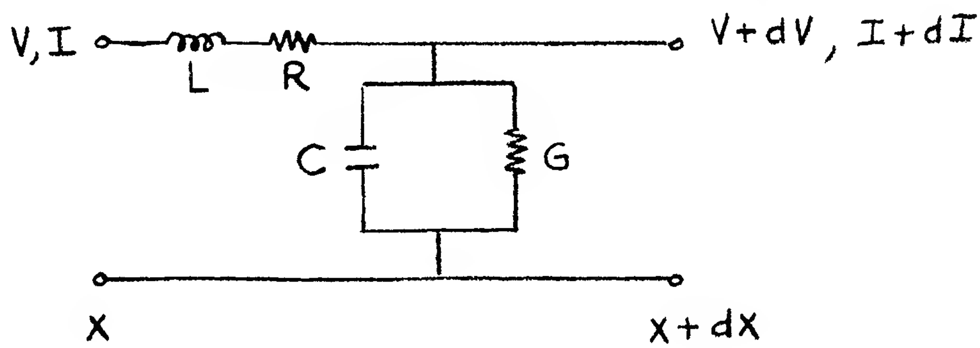


Scope Photos Taken During Field Test of Commercial Equipment. (Note lower traces carefully.)

SUPPLEMENT 1A

TRANSMISSION LINE BASICS (LAPLACE TRANSFORM METHOD)

A differential element of a two-wire line may be represented as shown. All parameters are per length. The usual



equations,

$$\frac{\partial V}{\partial x} = Ri + L\frac{\partial i}{\partial t}$$

$$\frac{\partial I}{\partial x} = Gv + C\frac{\partial V}{\partial t}$$

are written, and from them we get the "Telegrapher's Equation,"

$$\frac{\partial^2 V}{\partial x^2} = RGV + (RC + LG)\frac{\partial V}{\partial t} + LC\frac{\partial^2 V}{\partial t^2}$$

for V(x,t), the voltage between the lines, and a similar equation for I(x,t).

Consider the problem on a lossless line (R = G = 0). Then

$$\frac{\partial^2 V}{\partial x^2} = LC\frac{\partial^2 V}{\partial t^2}$$

or

$$V_{tt}(x,t) = a^2 V_{xx}(x,t) \text{ if } a = \frac{1}{LC}$$

Add the four necessary conditions (two for time, two for space) to solve a problem--say the shorted line of length L with $V(L,t) = 0$, $V(x,0) = 0$, $V(0,t) = F(t)$ (an applied voltage at $x = 0$), and $V_t(x,0) = 0$.

Transforming with respect to time, substituting the initial conditions and solving the resulting differential equation gives $V(x,s) = f(s) = K_1 e^{-\frac{sx}{a}} + K_2 e^{\frac{sx}{a}}$.

Transforming the remaining two space conditions and solving for K_1 and K_2 will give finally

$$V(s,x) = f(s) \left(\frac{e^{\frac{s}{a}(L - x)} - e^{-\frac{s}{a}(L - x)}}{e^{\frac{sL}{a}} - e^{-\frac{sL}{a}}} \right)$$

Multiplying numerator and denominator by $e^{-\frac{sL}{a}}$, and expanding the factor $(1 - e^{-\frac{2sL}{a}})^{-1}$ to $\sum_{n=0,1,2,\ldots}^{\infty} e^{-\frac{2snL}{a}}$ will eventually give

$$V(s,x) = f(s) \sum_{n=0,1,2,\ldots}^{\infty} (e^{-\frac{s(x+2nL)}{a}} - e^{\frac{s(x-2L(n+1))}{a}})$$

Now, using the property of Laplace Transforms that

$$L^{-1} \left\{ e^{-ks} f(s) \right\} = F(t-k) S_k = \begin{matrix} F(t-k), & t \geq k \\ 0 & , t \lessdot k \end{matrix}$$

we may write

$$V(t,x) = \sum_{n=0,1,2,\ldots}^{\infty} F(t-\frac{x+2nL}{a}) S_{\frac{x+2nL}{a}}$$

$$- F(t-\frac{x-2L(n+1)}{a}) S_{\frac{x-2L(n-1)}{a}}$$

The expression may be interpreted physically by letting $x = 0$, or $\frac{L}{2}$, or L, and, summing terms, one may see

that the voltage vs. time function imposed at $x = 0$ travels as a wave down the line with velocity "a", reflects from the end, travels back as a negative wave, and if the sending end is now an open circuit, doubles its magnitude (-), while the incoming wave superposes the outgoing wave, until the wave has completely left the vicinity of the sending end again. (Reference 3 in the Bibliography.)

The wave on a lossless line imposed, say, as a pulse, preserves its shape as it travels up and down the line, but when the problem is solved with R and $G \neq 0$, the waveform becomes distorted progressively, a much more difficult problem of dispersion.

ECL 193B

ENGINEERING CASE LIBRARY

ACCURATE LOCATION OF ARCING FAULTS ON PIPE-TYPE UNDERGROUND POWER CABLES

Part B

Evolution of a Method: The Design - Test - Redesign Cycle

"Failures, repeated failures, are fingerposts on the road to achievement. One fails forward towards success."

- Charles Kettering

PLAN OF ATTACK

Following his own ideas, John had already done some lab work on cables and had seen more field results by the end of 1963. On November 29, 1963, he wrote an over-all Interim Status Report where he described his aim:

> It became abundantly clear in April, 1962, that the impulse-reflection method was doomed to failure because of the statistical time lag of flashover at the fault.... We at that time summarily dismissed impulse-reflection techniques, even employing synchronized passive delay, from further consideration....
>
> The philosophy of the scheme under development at the present time is essentially simple. If a DC charge is gradually built up upon the cable from a source of relatively high impedance, the voltage at the fault will eventually be sufficient to cause its flashover. There will then propagate from the fault a wave of opposite polarity which, upon encountering the high impedance of the charging source, will be approximately doubled and reflected, and later, when again reaching the fault, will be reversed and reflected. This sequence of events will continue, producing, ideally, a square-wave train the period of which is a measure of the distance to the fault.
>
> To eliminate dependence on a knowledge of the velocity of propagation in the cable--which could not be expected to be known to better than a tenth of a percent--measurements can be made in both directions from the fault, using an unfaulted phase as the return conductor. A quick check on the precision of the measurements is possible by comparing their sum to a similar measurement made using a spark gap at the far

> end of the third phase. Any influence of time lag is completely eliminated, and the distance to the fault is obtained as a ratio, obviating a precise knowledge of the velocity of propagation.
>
> No particular novelty is claimed for the above--its potential usefulness is contingent upon its practical realization.

John added, "The decision was supported by laboratory trials on insulations of widely different high-frequency characteristics."

The time lag of flashover and the squarish wave train are shown in Appendix A as Exhibits 3A and 6A.

A DIFFERENTIATING NETWORK AND OTHER IDEAS

John decided he would differentiate the pulses in order to try to eliminate so much subjective judgment from interpretation. After all, the final technique was to be used by hard-pressed field maintenance men. The idea was both to voltage-divide--the scope had to be protected--and differentiate the pulses arriving from the fault's self-discharge. He asked for and was granted funds to build a 135 KV network with a rise-time of 10^{-9} seconds.

The year 1964--remember that John was working on many projects simultaneously--saw the construction of the network and much testing in the lab. Parasitic oscillations led to the insertion of damping resistors. A field test resulted in grading resistor flashover, due to a dv/dt greater than 10^{12} v/sec, not readily duplicated in the lab, and this unbalance in voltages ruined some of the network capacitors. Zener diodes were also tried, both to limit the signals and to introduce a threshold value in efforts to "clean out a lot of the hash." Another idea occurred--to separate positive and negative going pulses with use of more diodes. John decided he had to use high-quality vacuum capacitors to guard against breakdown and further serve to eliminate parasitic oscillations due to common capacitor lead inductance. (His 1964 progress report is shown as Exhibit 1B, Appendix B.)

In 1965, other work prevented full time attention but the new network was completed and tested in the laboratory with good results. Plans were made for field testing at Plymouth Meeting in 1966, when weather permitted.

DISAPPOINTING FIELD TRIALS

Instead of testing in Philadelphia, John was invited to be one of many participants at a series of tests held by Consolidated Edison in New York City in May of 1966. John's report on this event showed that, under severe environmental conditions, almost every conceivable method was attempted to locate faults imposed on one of Con-Ed's lines.

John said, "In one case the signals picked up by a certain tracer method were stronger on the water-main system supplying the fire hydrants in the area than on the cable pipe!" These tests went on until the early hours of the morning.

None of the methods, including John's, gave very good results. However, John's was one of the two most precise out of the dozen techniques and was the only one that gave any indication of the location of the arcing-type fault. Nevertheless, it was not anywhere as precise as John had hoped it would be. "The precision was some two orders of magnitude poorer than our target," said John, "and I began to feel that the original aims might be intrinsically unobtainable." (See the photo, Exhibit 2B, Appendix B.)

The scope records from the New York tests showed that the cable attenuation was introducing dispersion of the different Fourier components of the pulse forms, representing a loss of information. For a precision of a small number of feet on a circuit of many thousands of feet, terminal measurements, it now seemed, would have to be supplemented by field techniques--perhaps a hydraulic-timing or direct-audio scheme, using an arc-generated sound wave in the high-pressure oil.

In recovering from this disappointment, John reflected that, really, his lab tests had been quite good, that he had not had a chance to test in the field in a more careful manner, and that, in the last analysis, tests on known faults could lead to development of a set of curves giving indicated vs. actual distance. He decided to continue field testing on 13.8 KV paper-and-lead cable in the field rather than the low loss RG-8 polyethylene coax he had used in the lab.

A NEW NETWORK DESIGN

June 1967 saw another interim progress report. The field tests on the 13.8 KV cable were begun in spring, 1967,

but were interrupted and finally "due to circumstances, the cable at 'G' and Luzerne Streets, Philadelphia, became no longer available for testing." While the use of a differentiating, voltage-dividing network with "threshold clamping, amplitude-clipping, and polarity steering" gave much cleaner wave shapes, John still had trouble with flash-over and parasitic oscillation. These problems, combined with much lower output voltages than designed for, prevented attainment of the desired precision. But John had a few good photos to show.

In his reports, however, John wrote, "The comments arising from those oscillograms were about equally divided between partial solutions and new problems."

This June 1967 report concluded with a proposed plan to rebuild the coupling network with "substantially increased capacitance and with an improved arrangement of the semiconductor elements." Then there were to be more field tests on paper-lead cable, to be followed by testing with a simulated fault on the Plymouth Meeting substation pipe-type cable.

Figure 1B, Appendix B, shows the set-up used at this time and the network which John intended to modify.

PROGRESS TOWARD THE END

Other work again prevented full-time effort on the project, but John's December 1968 status report reflects a new optimism. (See Exhibit 3B, page 4B.) Use of an electronic counter was now proposed in order to avoid dependence on scope traces. The new network had been built and tested well in the lab.

The year 1969 saw additional lab testing and the acquisition of a counter. Plans were made for field testing in early 1970, when weather permitted. During the summer of 1970, field tests of the new network, using the counter, gave at last the results wanted. (The new network configuration is shown in Figure 2B, page 5B.)

Plans were made to demonstrate use of the technique to Transmission and Distribution personnel and recommend purchase of additional instruments by Service Maintenance.

Figures 3B, 4B, 5B in Appendix B, show some of the equipment developed as well as a field test being conducted by John Burns.

Figure 6B and Exhibit 3B, Appendix B, depict and briefly describe the final procedure as written up by John Burns in an instruction manual for use by field personnel.

APPENDIX B

RESEARCH PROJECT STATUS REPORT

PIPE-TYPE-CABLE FAULT LOCATING

Project No.: 4365

Project Engineer: J. J. Burns

Started: January 8, 1962

1964 Progress

W.O. 5299-923

Closed:

1st Quarter 1964:

High-voltage coupling network was constructed and modified to eliminate parasitic resonances. Very-high-speed clipping circuit was added to limit input to measuring device. Very promising oscillograms of manufactured fault on coaxial cable were obtained in the laboratory. (5/26/64)

2nd Quarter 1964:

Field tests on experimental pipe cable at Plymouth Meeting were conducted on May 5, using oscilloscope as indicator. Analysis of the oscillograms indicates that there was either flashover or dielectric breakdown in the coupling network during the cable discharge. Readable indication of the fault location was not obtained. The oscillograms show a much more marked deterioration of the slope of the reflected waveform than was experienced with the laboratory coax, a circumstance which may be partially due to the network failure. In addition, rather pronounced coupling of arc noise onto adjacent phases was observed.

Consideration is being given to the use of vacuum capacitors in the coupling network. (7/24/64)

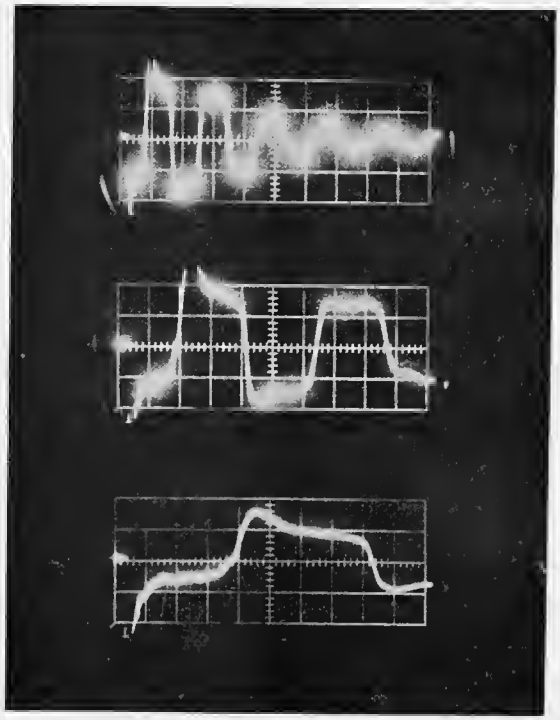
3rd Quarter

Network using 32-kv, 12-pf government-surplus capacitors was built which gave very low output voltage, but demonstrably correct time intervals when used on 3-kv coax setup in laboratory. Capacitors failed when network was impulsed with 60-kv from surge generator. Since one capacitor had previously been subjected to power arcs during F. M. Ekvall's vacuum-arrester investigations, its initial integrity is suspect. We now plan to use high-quality vacuum capacitors with adequate capacitance to give a larger output voltage. (12/8/64)

4th Quarter 110 hours $1,645.00

Expense authorization approved 12/29/64 for fabrication of divider, modification of fault and field testing at Plymouth Meeting.

Plan to conduct field tests approximately April 1, 1965. (1/2?/65)

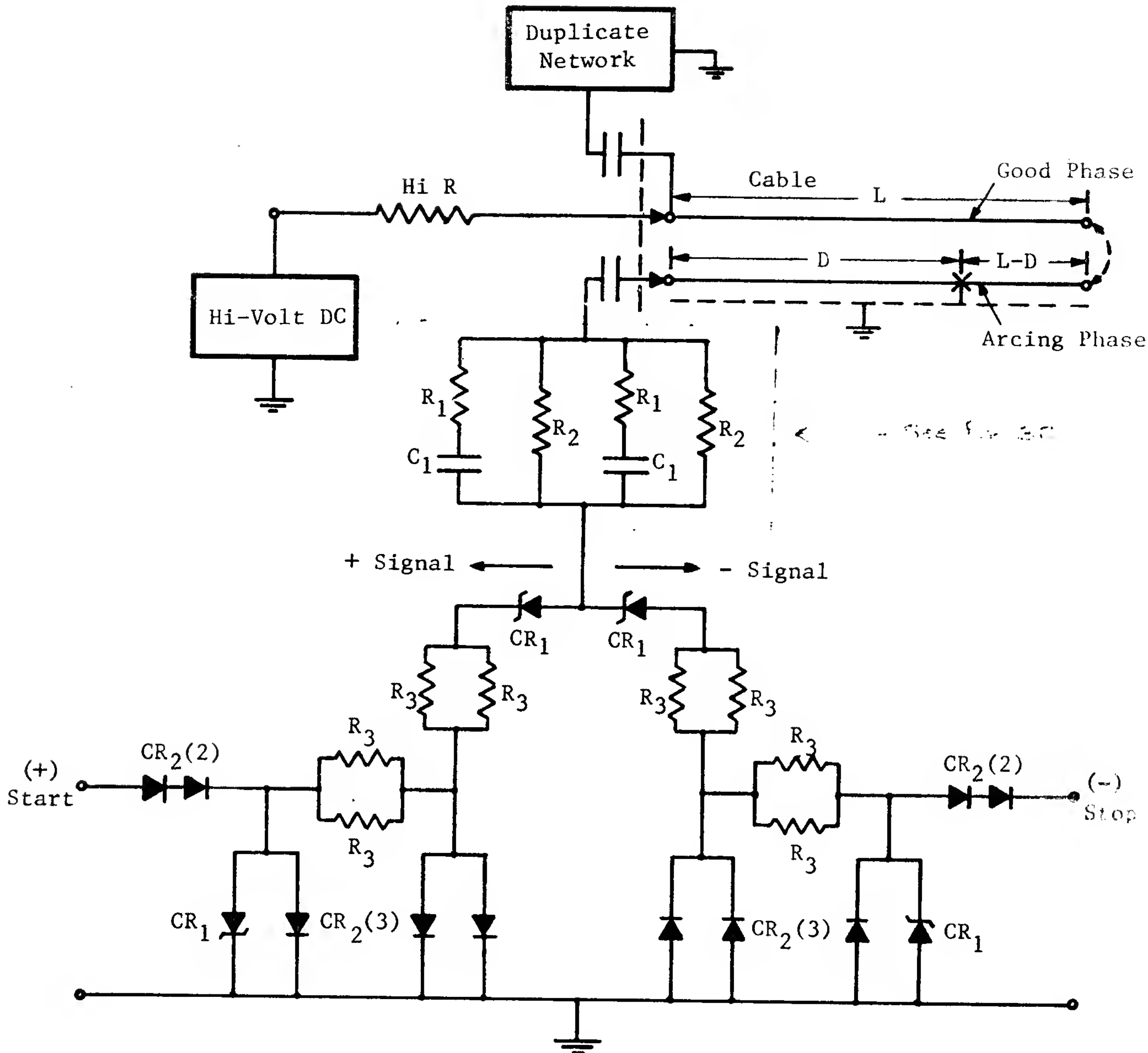


Scope Photo from 1966 New York Tests:

Data: Top: 50 μs/cm (H), 1 V/cm (V)
Middle: 20 μs/cm (H), 1 V/cm (V)
Lower: 10 μs/cm (H), 2 V/cm (V)

Note: Scope triggered when pulse from fault arrives. The indicated 2-way travel time is ≃ 40 μsecs. Fault was 8500 feet away. Indicated wave velocity ≃ 425 ft./μsec.

Exhibit 2B



Values:

C_1(2) Vacuum Cap., 100 uuf, 60 kv

R_1(2) Wirewound N.I. Resistor, 15 Ω

R_2(2) Resistor, 36 Meg, 50 w

R_3(8) Resistor, 50 Ω, 2 w

CR_1(4) Zener, 27 v, 50 w

CR_2(10) Diode, 1 a, 600 piv

Figure 1B: 1967 Network and Set-up

RESEARCH PROJECT STATUS REPORT

DEC. 3 1 1968

PIPE-TYPE CABLE FAULT LOCATING

Project No. 4365
W.O. No. 3111.4501
Project Engineer: J. J. Burns

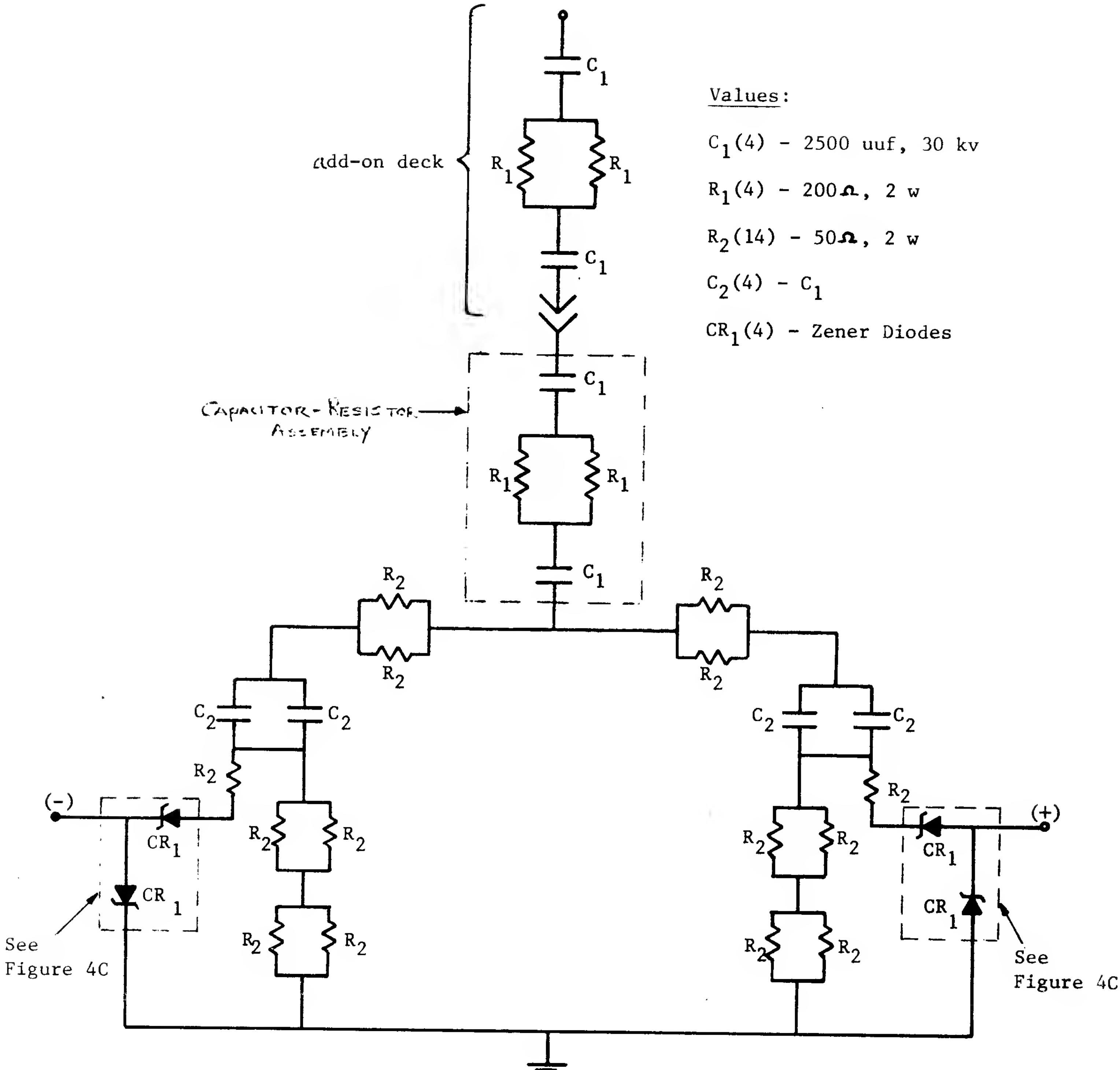
Requested by: Electrical Engineering
Service Maintenance
Started: January 8, 1962
Closed:

1968 Progress:

The high-voltage coupling network, featuring substantially increased capacitance and provision for optimizing the effective capacitance in relation to the breakdown voltage of the fault, has been assembled in final form and successfully tested on a variety of simulated faults.

Techniques for conditioning the output signal are essentially fully developed. Use of an electronic counter for transit-time measurement is visualized as the next step, from which measurements curves will be prepared indicating the relation between apparent and actual distance to the fault.

Study of a subsidiary problem, involving anomalous inaccuracies of the Morse-Newhall bridge, has been actively undertaken.



Values:

$C_1(4)$ - 2500 uuf, 30 kv

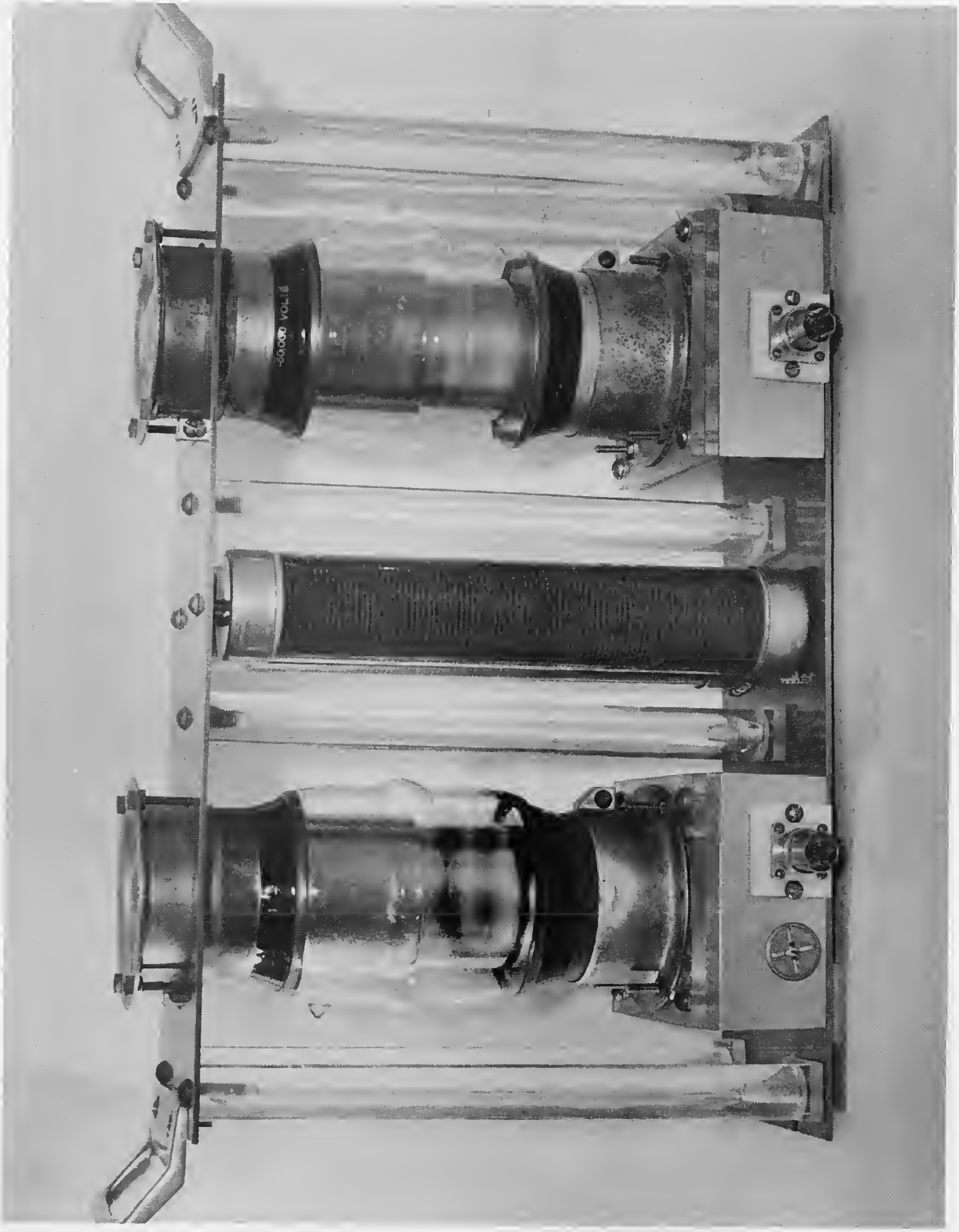
$R_1(4)$ - 200Ω, 2 w

$R_2(14)$ - 50Ω, 2 w

$C_2(4)$ - C_1

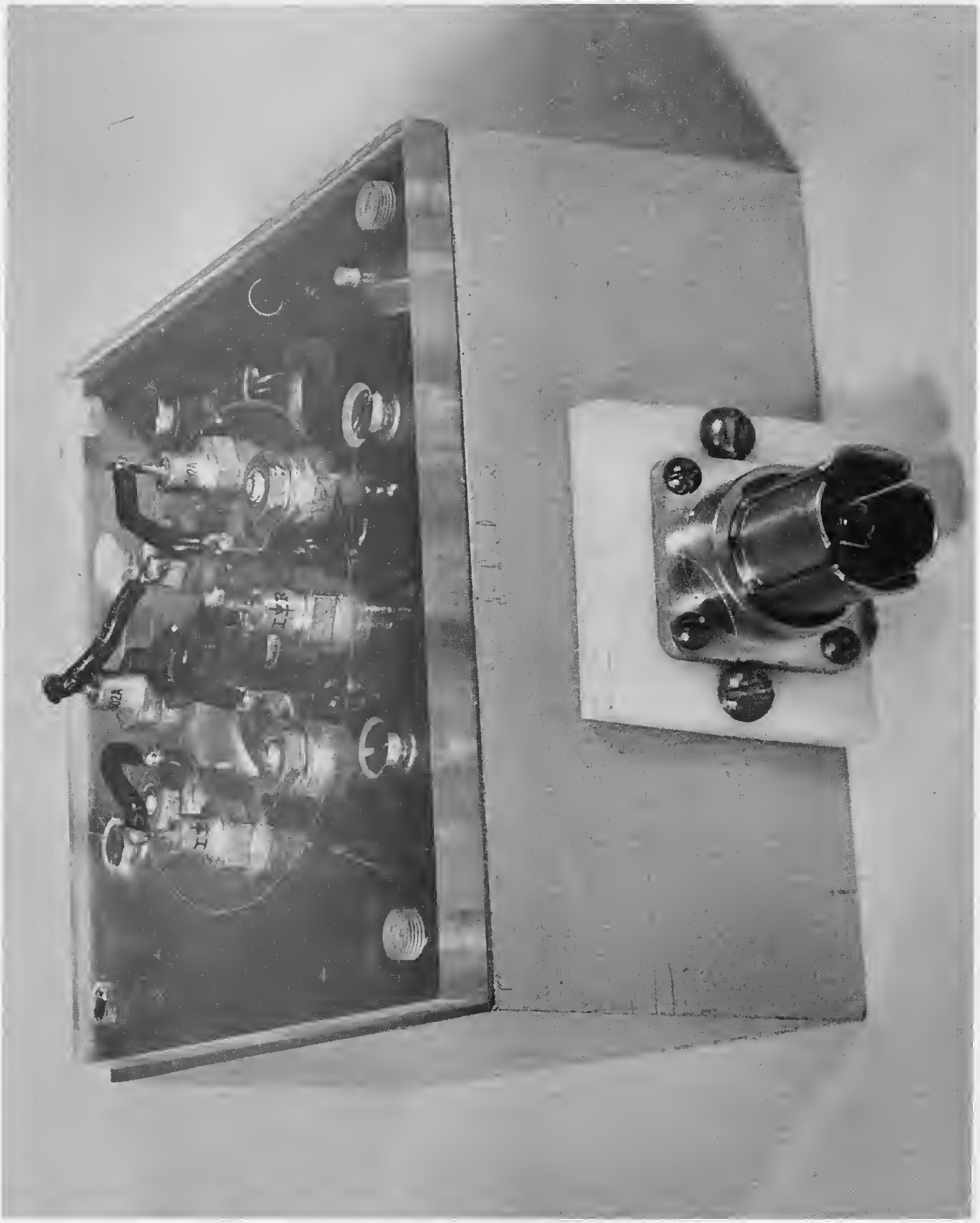
$CR_1(4)$ - Zener Diodes

Figure 2B : New Network



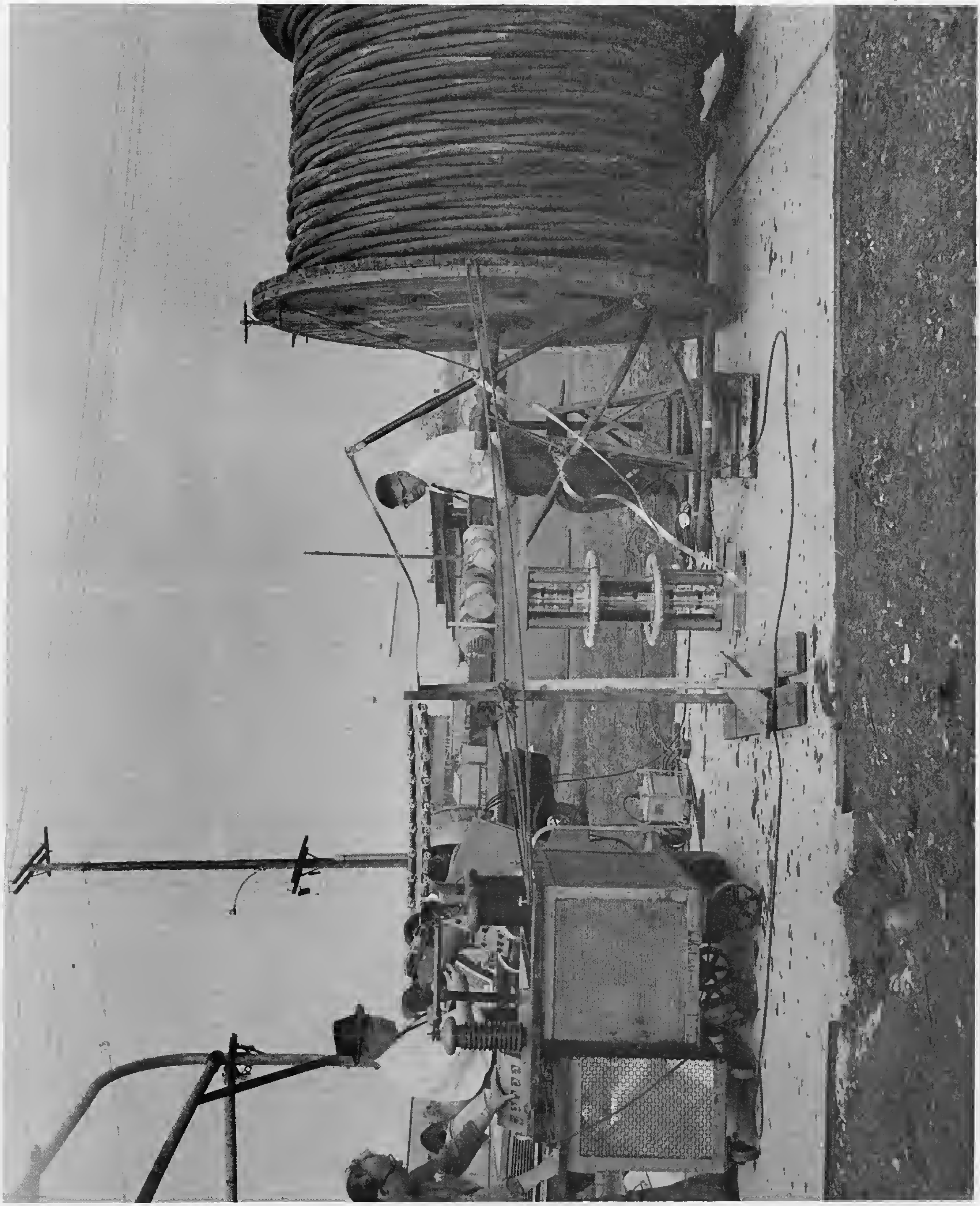
Coupling Capacitors and Grading Resistors Shown in Schematic Figure 2B.

Figure 3B



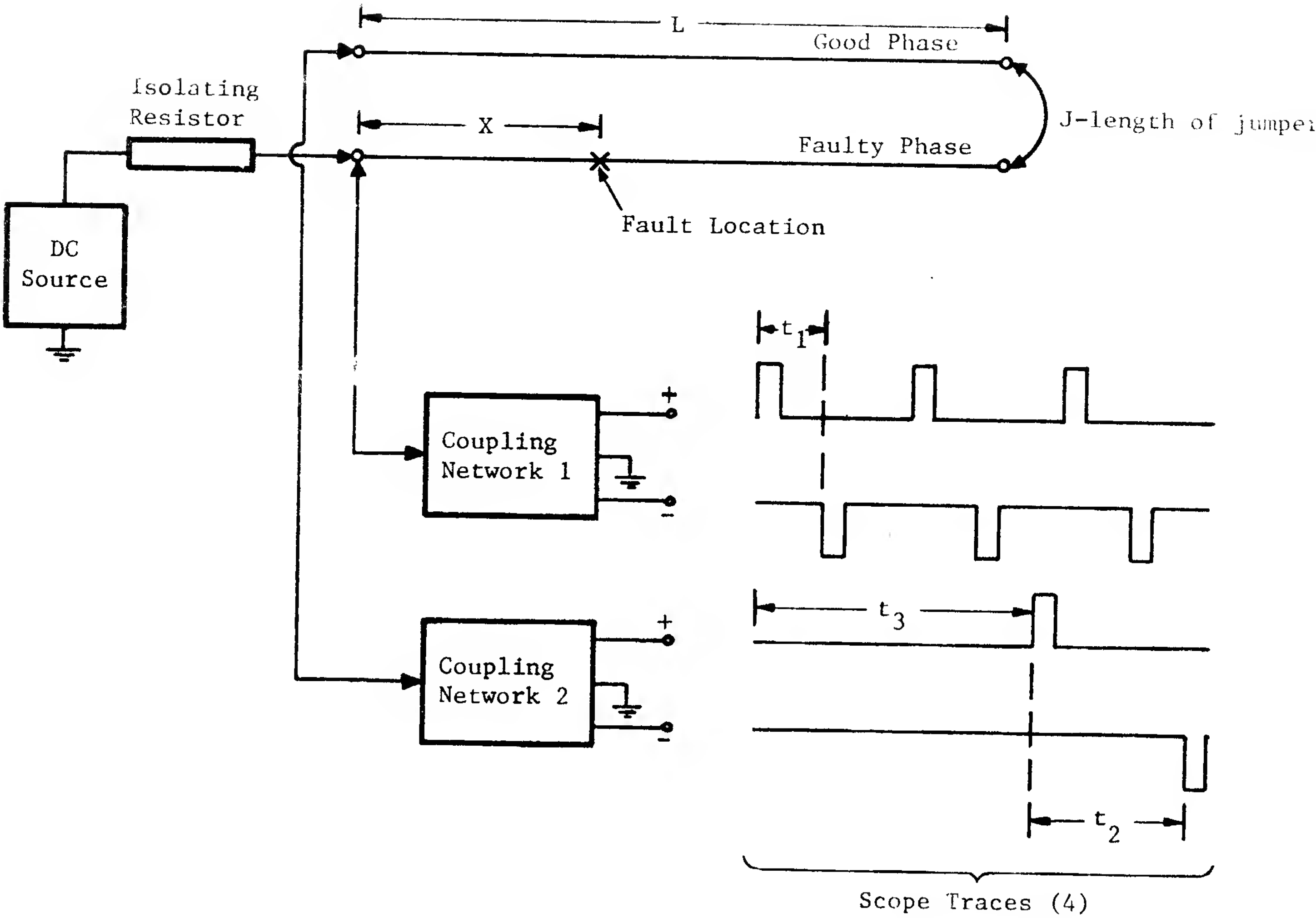
Zener Diodes Used in Network of Figure 2B.

Figure 4B



An earlier field test under way in 1966; John Burns, shown at right, assisted by other PE personnel. Early version of coupling network shown attached to cable.

Figure 5B



Timing:

t_1: Start on short-way (+); stop on short-way (-)

t_3: Start on short-way (+); stop on long-way (+)

t_2: Start on long-way (+); stop on long-way (-)

Figure 6B : Setup for Arcing Fault Location

EXHIBIT 1B

PROCEDURE FOR FAULT LOCATION

(BY JOHN BURNS, JULY 1970)

The most usual employment of the system for an arcing fault on a straight-forward, two-terminal line involves placing a jumper between the faulted phase and a good phase at the remote terminals of the line, and connecting a coupling network to each of these phases at the line terminals where the measurements are to be made. Care must be exercised in making the ground connection to the network so that no extraneous circuitry (supporting steel, station ground copper, or, especially, slip-on current transformers if such are present) is included in the loop comprising the pothead and the network; and that the ground strap connection is made to the actual sheath or riser pipe of the cable and not to an arbitrary piece of station ground copper. If there is apparatus, extensive bus work, or a transition to aerial construction connected at either of these locations, their connections should be lifted at the potheads.

The DC Test Set is connected, through an isolating resistor suitable for the test voltage expected, to either phase at the measurement end. (See Figure 6B.)

Connections are made from the network output terminals to the input patch panel and from there, in accordance with the proper diagrams, to the oscilloscope and counter. The four cables between the networks and the patch panel must be each of the same length, and, of course, properly identified at the patch panel.

The voltage of the DC Test Set is then brought up to a level sufficient to cause breakdown of the fault every few seconds. The oscilloscope controls are adjusted to provide a stable display in the "alternate" mode, which are examined for the possible presence of spurious information, in which case appropriate remedial measures are taken.

In accordance with the detailed instructions, connections to the counter are made in each of the specified modes to yield the three time measurements: t_1, t_2, and t_3. It is suggested that eight to ten readings be averaged for each value. It should be verified at this time that the constraint condition, $t_3 = (t_3 - t_1)/2$ is satisfied within the experimental error.

The treatment of these data depends upon the precision necessary for the particular localization, and upon the accuracy with which the actual cable lengths are known.

1. For a routine circuit fault, where location between manholes suffices, the distance to the fault is given as the product of t_1 and v', where v' is the effective "round-trip" velocity indicated on Curve I for the measured value of t_1. Since the other two measurements are not used in this rough method, the phase-to-phase jumper and lifting of terminal connections at the remote end are not necessary unless it is desired to have the "self-check" inherent in evaluation of the constraint condition.

2. For more refined calculation of the distance to the fault, the following five formulas are available: (for t's, see Figure 6B)

$$(1) \quad X = \left(\frac{t_1}{t_1 + t_3}\right) \cdot \frac{D}{2}$$

$$(2) \quad X = \left(\frac{t_1}{t_1 + t_2}\right) \cdot D$$

$$(3) \quad X = t_1 v'$$

$$(4) \quad X = \frac{D}{2} - t_3 v'$$

$$(5) \quad X = D - t_2 v'$$

Where: D = total length
$= 2L + J$

and: v' = effective "round-trip" velocity
(½ actual wave velocity)

It is to be noted that the first two formulations do not require prior knowledge of the effective propagation velocity, but, rather depend on an accurate knowledge of the actual length of the circuit; whereas the third formulation requires no knowledge of the total length of the line.

It is anticipated that as a body of experience with the method is accumulated, more refined and precise estimates of the effective velocity will be available, as will be a curve for correcting the time ratio (the terms within brackets in formulas 1 and 2) into almost identical but more precise distance ratios.

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2. Diggs, R. S., "Cable-Fault Locating Practices in Philadelphia," Electric Light and Power, October, 1951.
3. Churchill, R. V., Operational Mathematics, McGraw-Hill Book Company, Inc., New York, 1958 (2nd Ed.) pg. 121 ff.
4. Federal Power Commission, Underground Power Transmission, 1966.

INSTRUCTOR'S GUIDE

CASE TITLE: Accurate Location of Arcing Faults on Pipe-Type Underground Cables

RELATED UNDERGRADUATE CURRICULUM AREAS:

1. Engineering analysis and design methods (electrical engineering orientation).

2. Applied mathematics (transmission line equations, boundary value problems).

3. Signal conditioning methods (differentiating circuits, wave clippers, Zener diode applications).

4. Power system analysis (underground transmission line maintenance problems).

SYNOPSIS: Maintenance of underground transmission lines can be expensive and time consuming. A group discussion among engineers at the Philadelphia Electric Company resulted in the assignment of a young research engineer to study and evaluate all known methods for locating intermittently-arcing faults on underground cables and to develop an improved method. What appeared at first to be a relatively simple problem turned out to be one fraught with many difficulties. Theoretical transmission line analysis was useful but limited, and experiments both in the lab and in the field were necessary and sometimes very frustrating.

Discharging a pulse into the fault and timing its return (a radar-like method) was found to be unreliable in fixing the location of the fault. The investigator tried an alternative method--charging up the cable and allowing it to break down at the faulty point. Consideration of the transmission line phenomena involved resulted in formulae into which times gained from scope displays of waveforms travelling over both faulty and good phases could be substituted. Thus appropriate distances could be calculated.

QUESTIONS FOR THOUGHT AND DISCUSSION:

After reading Part A:

1. What events and trends initially motivated the company to begin the project on fault location?

2. Why was John Burns asked to attend the meeting which began this project?

3. Why was it felt necessary to locate faults with a precision of ± 0.1%, the design objective of the project?

4. What are the various methods for locating faults in UG cables? Discuss their advantages and disadvantages.

5. Note that both a literature search was made and also, at one time in the project, a consultant was called in to demonstrate his equipment. What were the results of these actions?

After reading Part B:

1. What part does transmission line theory play in John's approach to the problem? Could he have proceeded without a basic knowledge of such theory?

2. Exhibits 3B and 5B indicate a basic problem with the radar-type method. This caused John to develop a quite different method. Discuss this crucial point in the case study fully.

3. What was the reason for differentiating the pulses before scope display? Clearly show how differentiation occurs.

4. What other "signal processing" steps did John take to make timing of pulse travel easier? Discuss these.

5. Discuss the reasons why the project extended over a long period of time.

6. To what extent was John dependent upon others for the project's successful completion and to what extent was he largely independent?

7. Clearly identify the times during the project where you feel engineering judgment was exercised properly.